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An effective beamformer for interference suppression without knowing the direction

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ABSTRACT

This paper proposes an effective beamformer for uniform linear arrays of half-wave dipole antennas based on binary bat algorithm (BBA) by controlling complex weights (both amplitudes and phases) excited at elements in an array. The proposed beamformer can impose adaptive nulls at interferences without knowing directions in the sidelobe region by minimizing the total output power of an array, whereas the main lobe and sidelobe levels are maintained. To demonstrate this capability, the proposal will be evaluated in several scenarios, compared to a beamformer based on binary particle swarm optimization (BPSO).

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1. INTRODUCTION

In smart antenna systems, to significantly improve the ability of interference suppression, energy-saving and spectrum utilization in radar and wireless communications applications, array pattern synthesis has been taken into account in numerous research papers. Some pattern nulling methods including weight control, position-only control [1]–[3] and array thinning [4]–[6] have been adopted to suppress interferences with their benefits and drawbacks. In the wireless revolution, adaptive beamformers based on weight control methods for interference suppression are of great interest [7]–[9].

In excitation weight-based control methods, the simplest one is the amplitude-only control because the only controlled parameters are the amplitudes of each weight. Nevertheless, for this control, the main lobe cannot be steered; various kinds of nulls are placed less flexibly, too [10]. The phase-only control is another simple one due to only controlling phases. The superiority of phase-only control is the ease of steering the main lobe and the utilization of existing phased arrays without incurring additional costs [11], [12]. The complex weight control, which simultaneously adjusts both the amplitudes and phases of each weight, has been deemed to be the best performance for array pattern synthesis, compared to the two above controls. Due to requiring a complete set of a controller, an attenuator, and a phase shifter for each element, this control may be the most complex and expensive to implement. But in exchange, its flexibility and effectiveness are the most remarkable [11].

Recently, metaheuristic algorithms for optimization such as bat algorithm (BA), particle swarm optimization (PSO), and genetic algorithm (GA), which outperform classical optimization techniques, have all been proved to be effective global optimization algorithms to obtain optimal patterns [3], [10]–[12]. Among those, BA is superior to the other algorithms on the different types of benchmark functions as well as multiple engineering problems [13], [14]. Adaptive beamformers utilizing BA were first introduced in [15] and also successfully performed for uniform linear arrays in [10]–[12], [16]. The results in [10]–[12] show that BA-based beamformers have been proved to be completely superior to GA and accelerated PSO-based ones in respect of the pattern nulling. Although the proposals in [10]–[12], [16] are fast pattern nulling approaches, they are required to know the direction of interferences. Moreover, except for the solution in [16], weight vectors optimized by these beamformers are in the real number format while the excitation amplitude or phase of elements are commonly adjusted by digital attenuators and/or digital phase shifters. Therefore, real weight vectors necessitate quantizing before applying them to the digital attenuators or digital phase shifters, which leads to the quantization error and the perturbation of array patterns. To handle this problem, the solutions in [17] have utilized digital attenuators and/or digital phase shifters to suppress interferences; nevertheless, placing various nulls or the mutual coupling effect in these studies has been not considered yet.

In addition to the aforementioned beamformers which require the direction of arrival information of interfering signals, there are some kinds of beamformers for interference suppression without knowing the direction of interferences. The first one is a beamformer based on reference (or training) signals using adaptive algorithms, like the least mean square that does not require the direction of arrival information but instead uses the reference signals, or training sequences, to adjust the amplitudes and phases of each weight to match the time delays created by the impinging signals into an array [18]. To use these beamformers, however, reference signals must be generated [18], [19]. Another one presented in [20] is a data-dependent beamformer that needs no iterative computation and needs no prior information of the signals-of-interest's incident directions nor temporal waveforms; also, this beamformer is able to adaptively maximize the output power and "blindly" suppress dominant interference of any arbitrarily unknown direction. While the beamformer in [20] is based on the singular value decomposition to find weight vectors that aim to maximize the beamformer's output power and place nulls in the direction of interferences, the proposed beamformer is based on metaheuristic algorithms to find weight vectors that aim to minimize the total output power. Specifically, an effective beamformer (EBF) based on bat algorithm (BBA) to obtain optimal complex weights is proposed in this study with useful contributions as:

- An effective beamformer can impose nulls: i) at interferences from unknown directions while simultaneously suppressing sidelobes and preserving the main lobe and ii) in sidelobe regions while the main lobe is steered towards different directions.
- The proposed beamformer for uniform linear arrays of half-wave dipole antennas is evaluated with and without the presence of mutual coupling, where weights are optimized for digital attenuators and digital phase shifters.

2. PROBLEM FORMULATION

This study considers a uniform linear array. The array including M half-wave dipole antennas is demonstrated in Figure 1. The array factor of this array is worded as (1) [21]:

$$AF(\theta) = \sum_{m=1}^{M} I_m \, e^{j((m-1)dk\sin(\theta))} = \sum_{m=1}^{M} a_m \, e^{j((m-1)dk\sin(\theta)+\delta_m)} \tag{1}$$

where M is the total number of antenna elements, $I_m = a_m e^{j\delta_m}$ is the complex weight excited at m^{th} element, $k = 2\pi/\lambda$ is the wavenumber, λ is wavelength, $d = \lambda/2$ is the inter-element spacing. With $l = \lambda/2$ is the length of dipoles, the element pattern $EP(\theta)$ is given as (2) [18], [21].

$$EP(\theta) = \frac{\cos\left(\frac{kl\cos(\theta)}{2} - \cos\left(\frac{kl}{2}\right)\right)}{\sin\left(\frac{kl}{2}\right)\sin(\theta)} = \frac{\cos\left(\frac{\pi\cos(\theta)}{2}\right)}{\sin(\theta)} \tag{2}$$

Figure 2 shows 3D patterns of dipoles. The normalized pattern of a vertically polarized dipole demonstrated in Figure 2(a) can be acquired by using (2). Also, the pattern of a horizontally polarized dipole placed on the y-axis, which is demonstrated in Figure 2(b), is shaped by rotating the pattern in Figure 2(a). By using the pattern multiplication principle, the array pattern $P(\theta)$ can be expressed as (3) [18].

$$P(\theta) = EP(\theta)AF(\theta) \tag{3}$$

Besides, during transferring electromagnetic energy in antenna arrays, radiation characteristics, including impedance and radiation pattern, of an excited antenna element are affected by the presence of the other antennas, which is known as mutual coupling. This damaging effect considerably impacts array patterns, for instance, the main lobe direction, the sidelobe level (SLL), and the null depth level (NDL); therefore, it is very necessary to take account of mutual coupling effects during the design of adaptive beamformers for pattern nulling. To characterize mutual coupling, therefore, mutual impedance, coupling matrix, S-parameter, or embedded element pattern are widely employed [18], [21]. Thus, this study will utilize the mutual impedance calculated by the induced electromotive force method presented in [12] to model the mutual coupling effect.

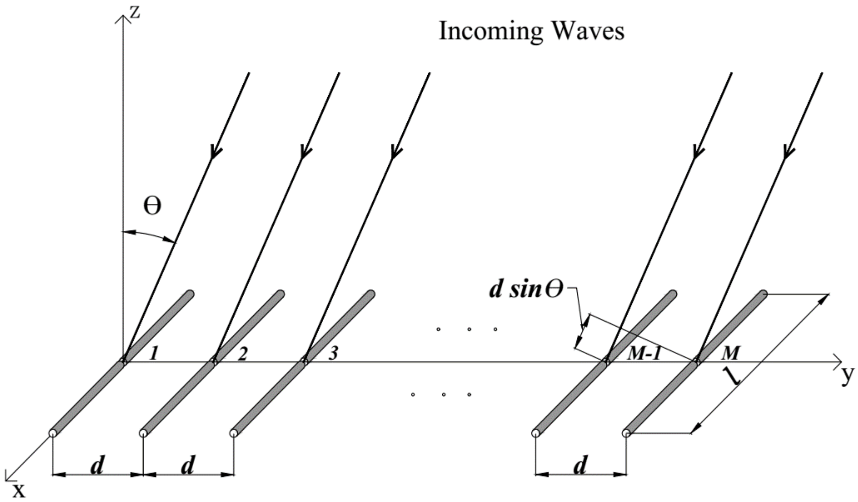

Figure 1. The geometry of M elements with spacing along the y-axis

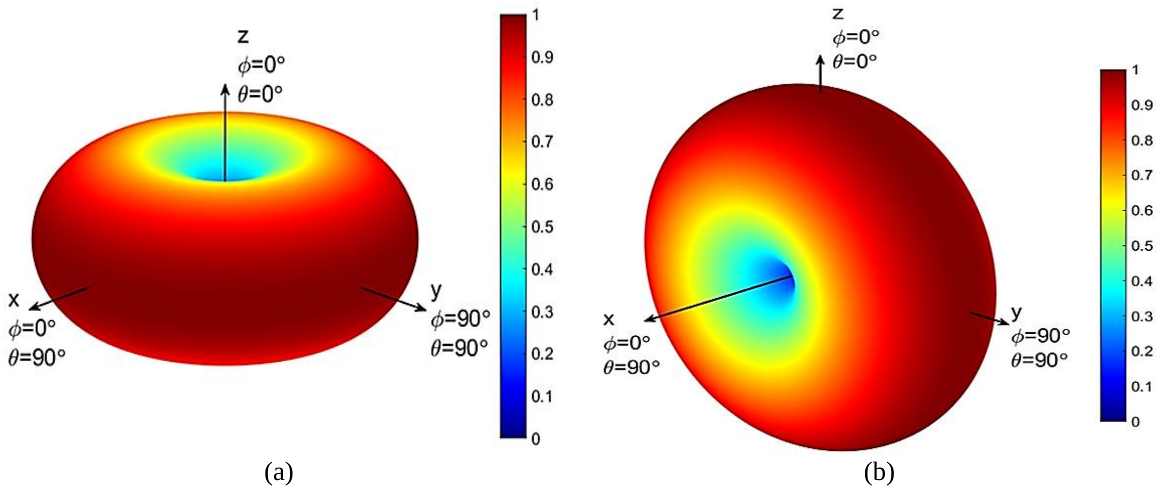

Figure 2. The normalized pattern of a vertically polarized (a) and horizontally polarized and (b) half-wave dipole

3. METHOD

3.1. The block diagram

The diagram of the proposed beamformer with M antenna elements ($M = 2N$) based on complex weight control is depicted in Figure 3. To acquire better efficiency in the process of obtaining the optimal pattern, the odd-symmetry of the phases for minimum weight perturbation should be used ($\delta_{-n} = -\delta_n$) [12]; consequently, the anti-symmetrical pattern across the main lobe direction is obtained. Besides, the amplitudes are chosen to be symmetrical through the array's center ($a_{-n} = a_n$) [10]. When $a_{-n} = a_n$ and $\delta_{-n} = -\delta_n$, (1) can be reworded as (4).

$$AF(\theta) = 2\sum_{n=1}^{N} a_n \cos(ndk\sin(\theta) + \delta_n) \quad (4)$$

According to (4) and the configuration given in Figure 3, it is apparent that the computational time and the number of weight controllers, and attenuators will be reduced by half.

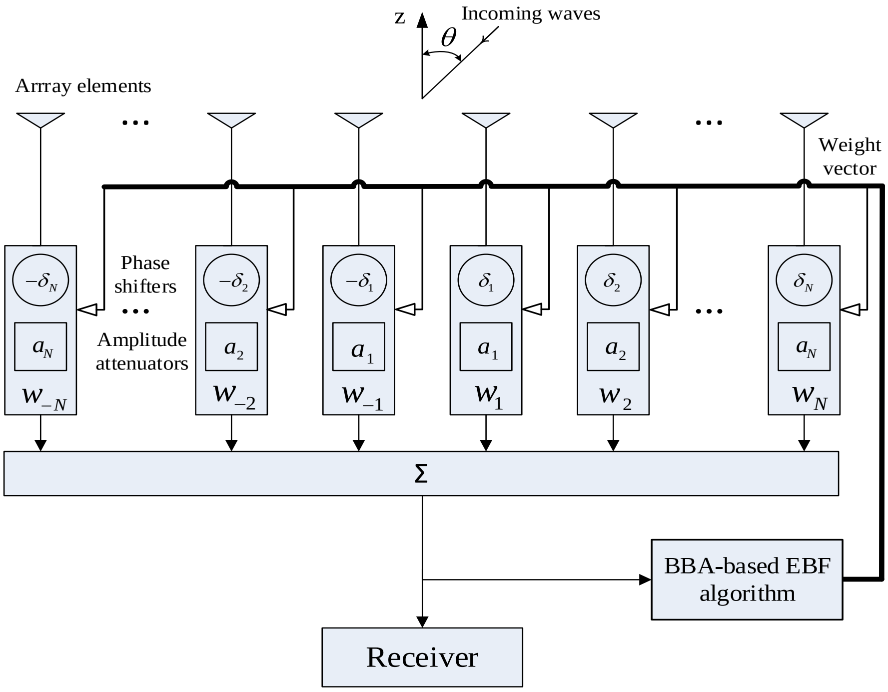

Figure 3. The diagram of a proposed beamformer

3.2. The objective function

The objective function in this proposal is developed for the receiver, but this development is similar for the transmitter. The proposed beamformer requires suppressing interferences while maintaining the main lobe and sidelobes at a specified level. This means that a problem required to solve is a constrained optimization problem. By applying the penalty method in [22], the objective function to solve this problem can be formulated as (5) [23]:

$$F(w, \xi) = \frac{1}{\xi}[f(w) + \xi P_e(w)] \quad (5)$$

where a penalty parameter ξ, which affects maximum SLL, NDL, and the main lobe, is chosen by the simulation scenario in subsection 4.1.

Typically, the desired signal and interferences simultaneously arrive at the receiving arrays. Assuming that the direction of the desired signal and interferences are entered in the main lobe and sidelobes respectively. The sub-total power of the desired signal will remain unchanged if the main lobe is preserved and the sidelobes are kept at a specified level. Therefore, the total output power of an array will be minimum only when the sub-total power of interferences is minimized. Therefore, the term $f(w)$ used for keeping the desired main lobe is expressed as (6):

$$f(w) = \sum_{\theta=-\frac{1}{2}\theta_{FNBW}}^{\frac{1}{2}\theta_{FNBW}} |P_o(w, \theta) - P_d|^2 \quad (6)$$

where P_d and $P_o(w, \theta)$ are corresponding to the desired optimized pattern and the optimal patterns using BBA in [24] or binary particle swarm optimization (BPSO) in [25]; θ_{FNBW} is the elevation angle at the first null beamwidth (FNBW). The term $P_e(w)$, which is to impose nulls at interference's directions, is defined by the total output power of all receiving signals including the desired signal and interferences. This power with signals having elevation angles θ_i and voltages s_i are defined as (7) [26]:

$$P_e(w) = \left|\frac{1}{\sum_{m=1}^{M} w_m} \sum_{i=1}^{N_{sig\_int}} s_i P(w, \theta_i)\right|^2 \quad (7)$$

where $P(w, \theta_i)$ is the pattern for i^{th} signal, N_{sig_int} is the total number of incoming signals, and M is the total number of antenna elements ($M = 2N$).

3.3. The proposed algorithm

The proposed algorithm is based on the basic BBA presented in [24]. The algorithm flowchart for effective beamformers is displayed in Figure 4. The termination conditions are chosen as maximum iterations in simulation scenarios apart from the determination of the computational time in subsection 4.2.

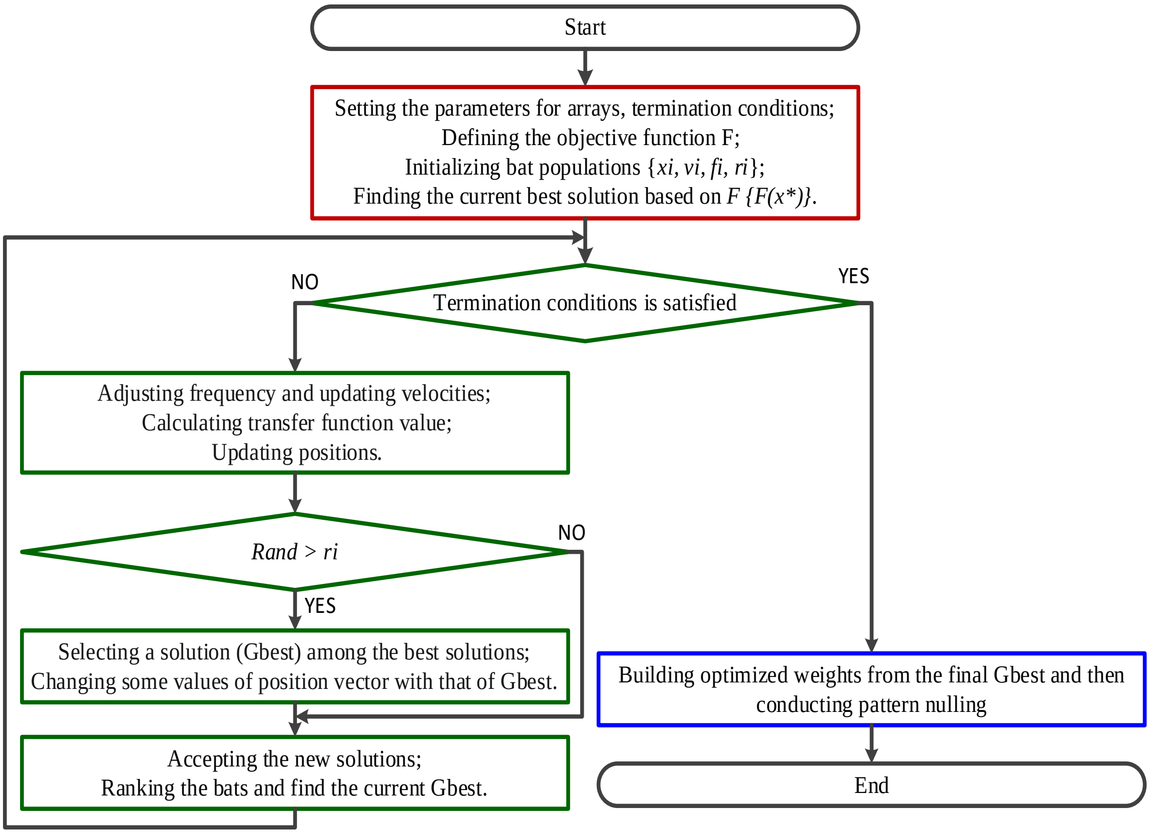

Figure 4. The algorithm flowchart of the proposed beamformer

4. RESULTS AND DISCUSSION

Parameters for scenario simulations are set as: a uniform linear array of half-wave dipole antennas includes 20 (2N) elements; the power of the desired signal is 0 dB; the phases and amplitudes of each weight vary in [-5°; 5°] and [0;1] respectively; P_d is the pattern using the Dolph-Chebyshev method with SLL= -30 dB. The population of BBA and BPSO are randomly initialized except for the first solution initialized by the weights obtained by the Chebyshev method. The initial parameters for the optimization algorithms are as:

- BBA: $f_{min} = 0$ and $f_{max} = 2$; $A = 0.25$; $r = 0.1$ [24].
- BPSO: $C_1 = C_2 = 2$; W is linearly decreased from 0.9 to 0.4; max velocity: 6 [25].
- The transfer function is V-shaped [24], [25].

The flexibility and capability of the proposed beamformer to suppress interferences have been investigated via the six scenario simulations. Moreover, the results of all simulation scenarios are the average values of 200 Monte Carlo simulations apart from the first scenario which is 100 simulations.

4.1. Penalty parameter ξ in the objective function

The first scenario determines ξ which is an unknown parameter in the objective function. In most cases, the signal-to-interference ratio (SIR) continuously varies to choose the appropriate value of ξ. In this scenario, BBA-based EBF has been employed to adaptively impose a null when an interference emerges at the sidelobe peak ($\theta = 14°$) of -30 dB Chebyshev pattern with $\xi = [1, 10^9]$ and $SIR = 0$ dB, -10 dB, -20 dB, -30 dB. Consequently, Figure 5 depicts four characteristics with $pop = 500$ and $iter = 10$, including the NDL at 14° in Figure 5(a), maximum SLL in Figure 5(b), half-power beamwidth (HPBW) in Figure 5(c), and FNBW in Figure 5(d).

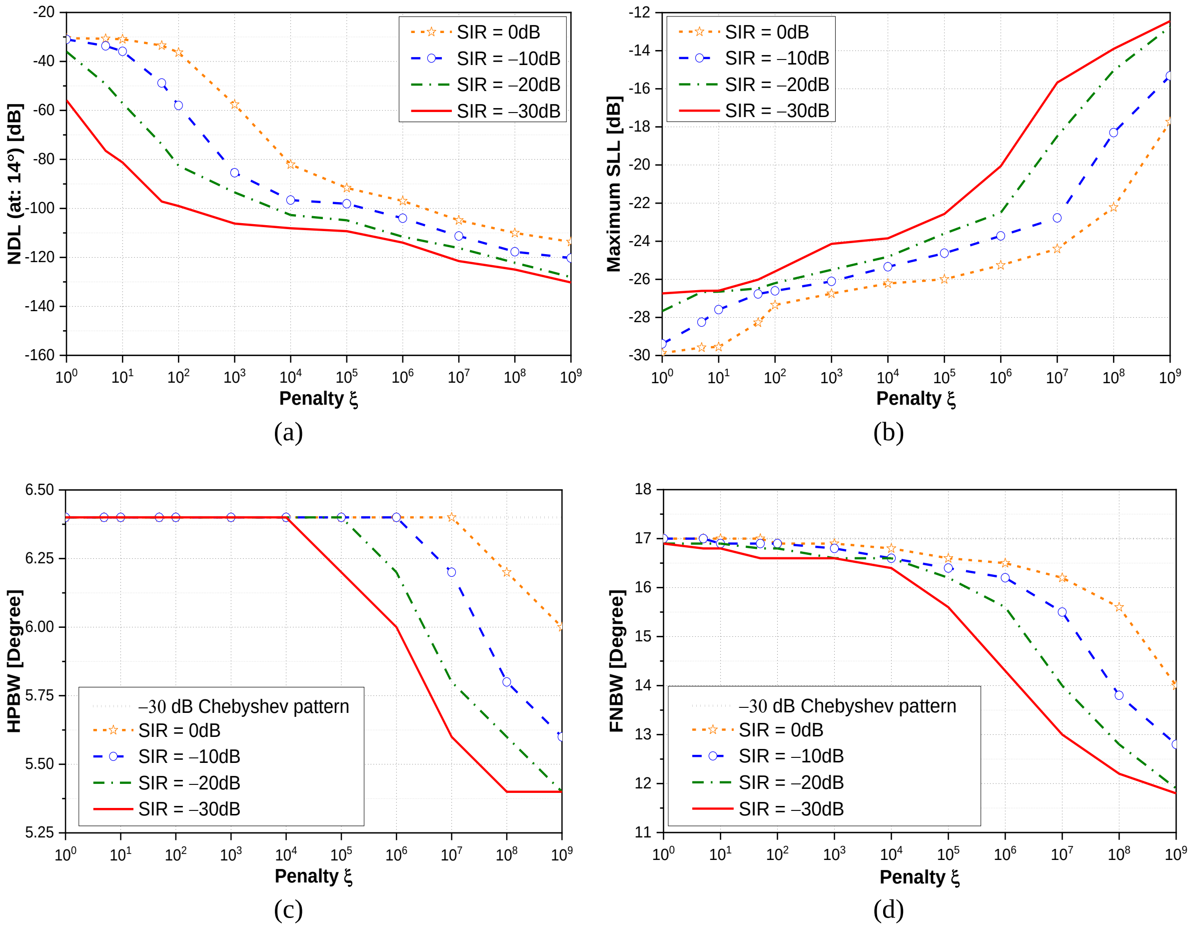

Figure 5. NDL at 14° (a) maximum SLL, (b) HPBW, (c) and FNBW, and (d) with different ξ values

The results show that the larger the value of ξ, the larger the maximum SLL and the deeper the null at 14°; moreover, the HPBW and the FNBW of optimized patterns also considerably change when ξ is big enough. To balance the trade-off between maximum SLL and NDL, and to maintain the main lobe HPBW and FNBW, ξ should be 10^4, 10^3, 10^2, 10^1 corresponding to SIR $= 0, -10, -20$, and -30 dB respectively. For illustrative purposes, $\xi = 10^1$ with SIR $= -30$ dB is set for the next scenarios.

4.2. Convergence characteristics

This scenario presents the convergence characteristics of BBA-based EBF by adaptively imposing nulls when an interference emerges at $\theta = 14°$. Firstly, the value of the objective function of two EBFs with $pop = 100$ and $ite = 100$ is displayed in Figure 6. The computational times of EBF based on BBA and BPSO to get the same value of the objective function ($F < 1.1$) are 0.35 seconds and 11.68 seconds respectively on a laptop (CPU Intel i5-8250U, 12 GB RAM, and MATLAB 2020a). It is apparent that BBA-based EBF has been faster than the BPSO-based one.

Secondly, Figure 7 shows the value of the objective function of BBA-based EBF with different population sizes. This EBF has taken 30, 15, 5, and 2 iterations to nearly converge ($F \leq 0.13$ dB) corresponding to $pop = 50, 100, 200,$ and 500 respectively. To evaluate the effective null-steering capability, the other scenarios will be simulated with $pop = 200$ and $ite = 5$.

4.3. Adaptive null-steering capability

This scenario presents the adaptive null-steering capability of the proposed beamformer. Figure 8 depicts optimized patterns when assuming an interference emerges at 14°. The optimized pattern of BBA-based EBF preserves most of the Chebyshev pattern characteristics including HPBW (6.4°) and SLL (-30 dB) except for the maximum SLL$= -25.99$ dB and NDL at $14° = -72.5$ dB. Additionally, Figure 8 indicates that BBA-based EBF has outperformed BPSO-based one about NDL and maintaining SLL.

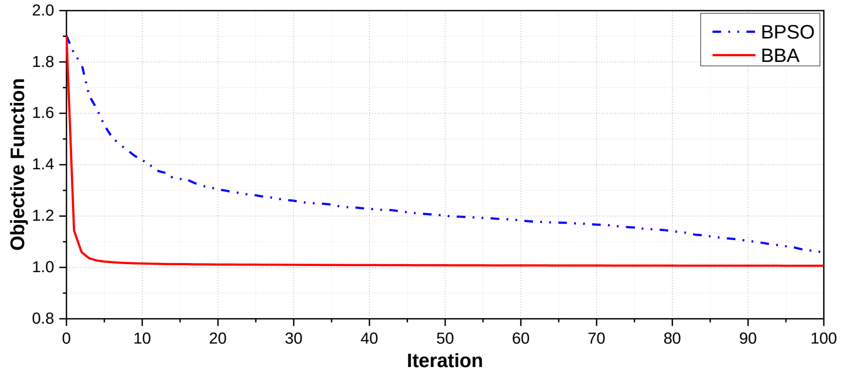

Figure 6. The comparison of the objective function of two EBFs

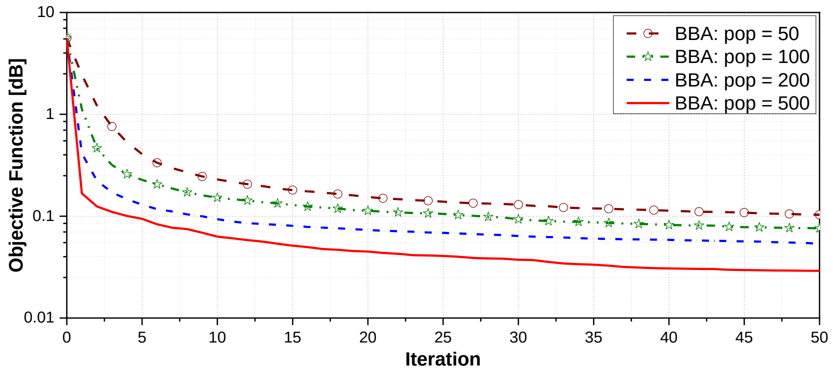

Figure 7. The objective function of two EBFs with different population sizes

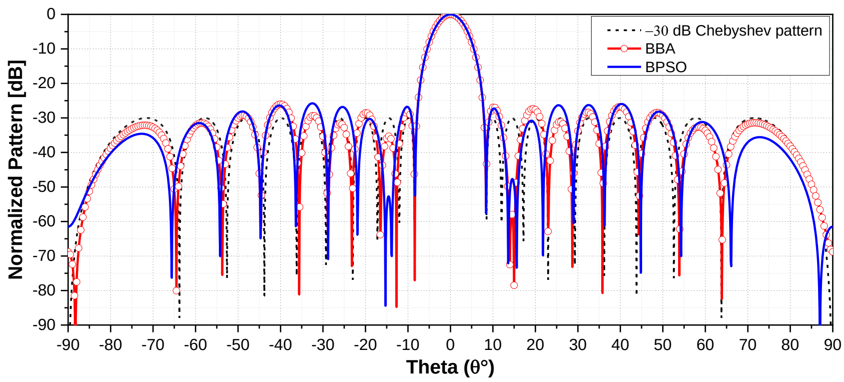

Figure 8. Two optimized patterns when an interference emerges at 14°

In the last two cases, Figure 9 and Figure 10 illustrate optimized patterns when interferences come from multiple and a range of directions respectively. The results indicate that nulls have been exactly set in the direction of interferences; moreover, BBA-based EBF has been better than BPSO-based one related to keeping SLL and imposing nulls. Detailed results for maximum SLL and NDL have been summarized in Table 1.

4.4. Optimized patterns when considering mutual coupling effects

This scenario considers mutual coupling effects by using the mutual impedance method to obtain optimized patterns depicted in Figure 11. The results show that multiple nulls are placed successfully in the direction of interferences but NDLs are shallower. Detailed results taking account of mutual coupling for the cases of pattern nulling have been displayed in Table 1.

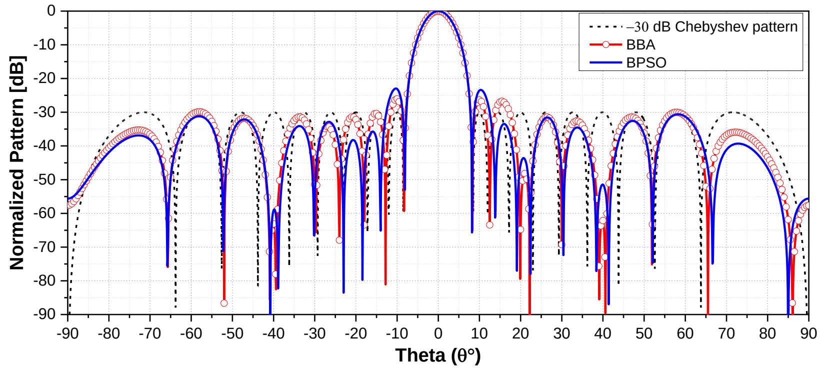

Figure 9. Two optimized patterns when three interferences emerge at -40°, 20°, and 40°

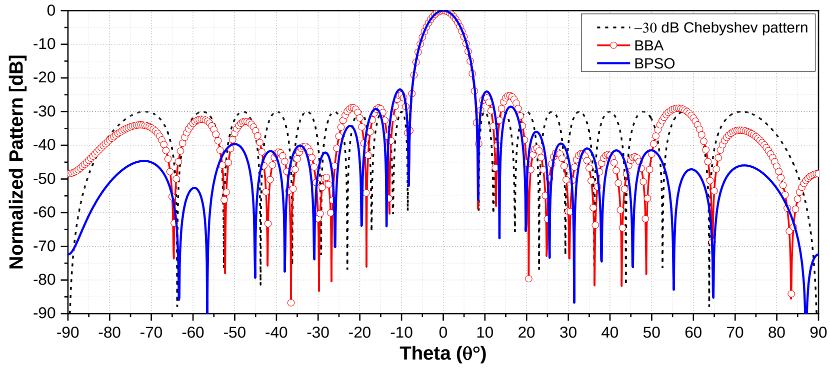

Figure 10. Two optimized patterns when interferences emerge from 20° to 50°

Table 1. Maximum SLL and NDL of optimized patterns are demonstrated in Figures 8 to 10 and subsection 4.4

Figure	Parameters	BPSO (dB)	BBA (dB)	
		Ideal	Ideal	Mutual coupling
8	NDL at: 14°	-51.64	-72.50	-64.16
	Maximum SLL	-25.77	-25.99	-25.75
9	NDL at: -40°	-59.07	-63.11	-51.89
	20°	-45.55	-64.81	-60.33
	40°	-51.47	-62.11	-50.77
	Maximum SLL	-22.97	-26.03	-25.42
10	Maximum NDL	-86.74	-81.78	-61.55
	Minimum NDL	-35.99	-40.86	-37.70
	Maximum SLL	-22.97	-26.03	-24.60

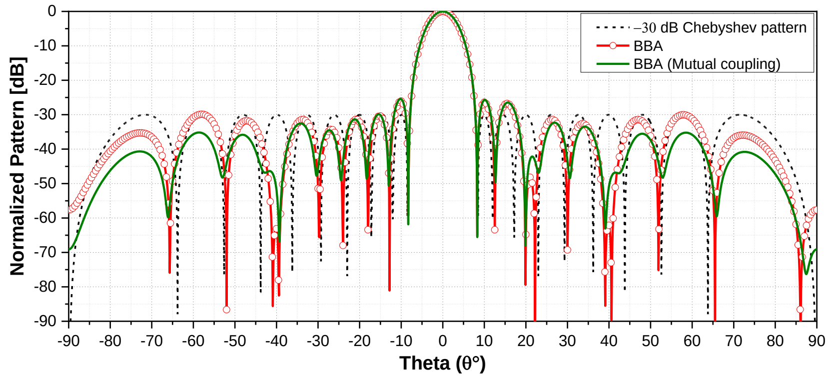

Figure 11. Optimized patterns when considering mutual coupling effects (nulls at -40°, 20°, and 40°)

4.5. Optimized patterns in the absence of interferences

This scenario evaluates the proposed beamformer without any interference. Figure 12 demonstrates optimized patterns that have been almost similar to the -30 dB Chebyshev pattern. This means that two EBFs still have maintained the main lobe while keeping SLL at $-30\ dB$ when no interferences emerge.

4.6. Optimized patterns the steered main lobe

The main lobe of the proposed beamformer not only is limited to the fixed direction as in the above scenarios but also can be steered. This is accomplished by steering the main lobe towards the desired direction before performing the aforementioned processes. Figure 13 demonstrates three pattern nulling cases in subsection 4.3 with the main lobe steered towards 5°. The results prove that interferences can be effectively suppressed, which is similar to the scenarios illustrated in subsection 4.3.

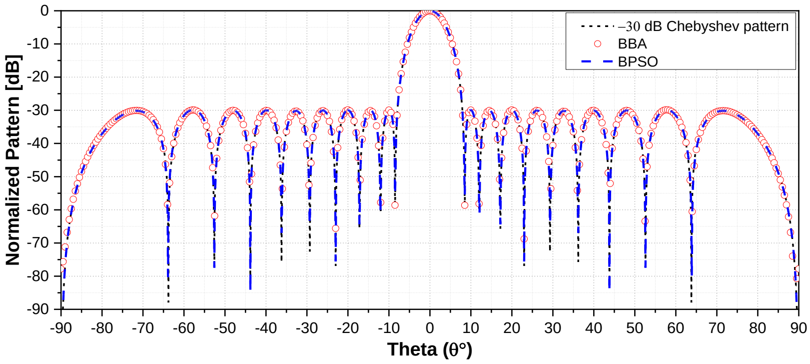

Figure 12. Optimized patterns when no interferences emerge

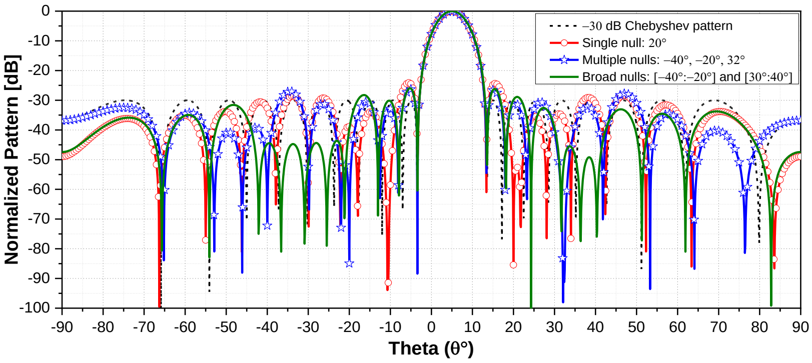

Figure 13. Optimized patterns with the main lobe steered towards 5°

5. CONCLUSION

This paper has proposed a BBA-based effective beamformer using complex weight control for uniform linear arrays of half-wave dipole antennas. Several scenarios have verified the efficiency of the proposed beamformer through convergence characteristics and the interference suppression capabilities without knowing directions in sidelobe regions. The other array geometries, simultaneously steering multiple main lobes, the resolution of digital attenuators and/or digital phase shifters, and the direction of interferences entering the main lobe should be considered in future works.

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